

AD618375

R 306 SUPPLEMENT

Technical Report

CORROSION OF MILD STEEL
IN CONCRETE

August 1965

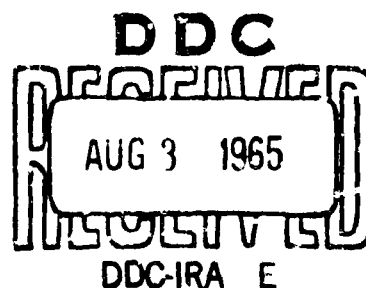
33-P
20

2.00

0.50



U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California



ARCHIVE COPY

**Best
Available
Copy**

CORROSION OF MILD STEEL IN CONCRETE

Y-R007-05-01-012

Type C Final Report

by

Donald F. Griffin

ABSTRACT

In a research effort to determine the fundamental cause of deterioration of certain concrete buildings in a marine environment, the author has shown that sea salts can accumulate in a building wall exposed to airborne sea spray in quantities sufficient not only to deteriorate the concrete but also to cause the reinforcing steel to rust and thereby expand with enough force to crack the concrete.

In small reinforced concrete walls sprayed with sea water once each morning, the same destructive phenomena has occurred at the Laboratory within a period of 2 years that occurred in about the same length of time to concrete buildings on the Pacific Ocean atolls. The concrete has cracked severely along the lines of the reinforcing steel.

In order to reduce the adverse effects of salt and increase the life of a reinforced concrete building in a marine environment, no salt water should be added to the concrete at the time of mixing the concrete. Corrosion of the reinforcing steel will be delayed if the initially salt-free concrete is of high quality, with low permeability and a low water-cement ratio. The greater the depth of embedment of the reinforcing steel (taking practical considerations and economy into account), the greater will be the delay of salt penetration to it; and the increased depth of cover will provide greater resistance to rupture by the pressure induced by the building of corrosion products on the steel.

This report supplements and extends Technical Report R-306, "The Effect of Salt in Concrete on Compressive Strength, Water Vapor Transmission, and Corrosion of Reinforcing Steel."

Qualified requesters may obtain copies of this report from DDC.

Release to the Clearinghouse is authorized.

The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

INTRODUCTION

Portland cement concrete reinforced with steel has been used extensively by the Bureau of Yards and Docks for land-based naval structures. Some structures located in a marine atmospheric environment have suffered more or less progressive deterioration.¹ Such deterioration occurred because of the adverse effect of a marine environment. The degree of deterioration has been influenced both by the quality of the concrete and by the severity of the marine environment. Corrosion of steel reinforcement in concrete presents problems in terms of aesthetics, safety, and economics.

NATURE OF CONCRETE

The study of corrosion must relate the response of a metal to the environment in which it is located; it must also take into account changes that may occur in that environment. For steel embedded in concrete to corrode, the same fundamental processes necessary for corrosion must exist within the concrete as would exist in any environment where corrosion of steel occurs. The particular form and rate of corrosion will depend upon a number of variables.

In contrast to other construction materials, concrete is a "living" material. Formulated with inert aggregate (sand and gravel), portland cement, and water, the hardened concrete continually breathes moisture in and out in order to maintain balance with the ever-changing relative humidity of its ambience. The movement of moisture in concrete is not a simple phenomenon.²

It is the ability of concrete to absorb free moisture from an external source that is primarily responsible for altering the internal environment of the concrete. A concrete with a higher cement content and a lower water-cement ratio will have a lower rate of moisture exchange with the atmosphere.³ Therefore, in an ambience of fluctuating relative humidity, such concrete will be more stable than one with a lower cement content and a higher water-cement ratio. These dynamic phenomena are important to understanding corrosion of embedded steel and the effects on concrete.

CORROSION OF STEEL IN CONCRETE

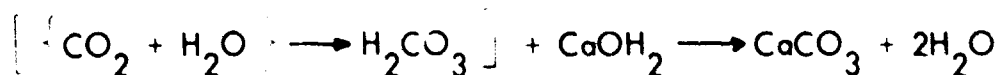
Mechanism of Corrosion

In any environment the basic mechanism of corrosion is in principle an electrochemical action. For corrosion to occur there must be a source of oxygen and a flow of electricity between certain areas of a metal surface through a solution capable of conducting the electric current. The conductive solution, known as the electrolyte, may be any liquid that contains electrically charged atoms or groups of atoms. Any free water in concrete will serve as an electrolyte; generally, however, the greater the number of ions per unit volume of electrolyte, the greater will be its capacity to conduct electricity.

Salt-free concrete has a pH of about 13 (highly basic), and under this condition embedded steel becomes passive. This is accomplished by the build-up of a tough, impermeable corrosion film on the steel. Chlorides entering the concrete lower the pH, and the chloride ions destroy this passive film; this favors the hydration of metal ions and increases the ease with which metal ions enter into solution, thus promoting the corrosion of the steel reinforcing bars.

The electrochemical action involved in corrosion causes dissolution of a metal at anodic areas, where the electric current leaves the metal and enters the electrolyte. The anodic areas may shift from time to time, permitting substantially uniform corrosion to occur. Corrosion products occupy a greater volume than the parent metal and produce pressures which crack and spall the concrete. This build-up of corrosion products on the metal can exert forces up to about 4,700 psi on the concrete.⁴

Effects of processes involved in carbonation, although perhaps exerting minor influences on the corrosion of steel in concrete, should not be overlooked. The carbon dioxide in the air enters the concrete and reacts with free moisture present to produce carbonic acid. The carbonic acid lowers the pH of the concrete, thus, endangering the integrity of the passive corrosion film on the steel. In addition, the carbonic acid reacts with the calcium hydroxide in the hydrated cement to form calcium carbonate plus twice as much free moisture as had combined with carbon dioxide to form carbonic acid; i.e.,



This additional free moisture may migrate farther into the concrete or toward an outer surface, depending upon the moisture equilibrium within the concrete and between the concrete and its ambience.

Role of Salts

There are many types of salts, and they react with metals differently. Sodium chloride dissolved in water forms a neutral solution normally less corrosive than solutions of acid salts, acid-oxidizing salts, or alkaline-oxidizing salts.⁵ Moreover, solutions of various chloride compounds* at equal normalities have the same number of chloride ions present; yet each solution of a different chloride compound causes a different corrosion rate for any given degree of equal solution normality.⁶

LABORATORY EXPERIMENTATION

In an investigation to determine the effect of sodium chloride and sea spray on reinforced concrete, the Laboratory has conducted a series of experiments to develop information on the separate effects of salt in concrete on compressive strength, water vapor transmission, and corrosion of the reinforcing steel. The experiments are reported in References 3 and 7. The present study supplements preliminary information on continued observations of long-term experiments on (1) the effect of depth of cover on corrosion of embedded steel, and (2) the effect of sea-water spray on reinforced concrete walls.

Depth-of-Cover Series

A number of concrete specimens, 6 inches in diameter by 6 inches long, for each of two different water - cement ratios (0.444 and 0.702) were prepared with corrosion-detection probes of mild steel.³ No salt was used in this experiment. The specimens were sealed in wet cups³ and stored in 50% RH at 73.4°F. Measuring from the bottom surface of the specimen, the probes had depths of concrete cover of 1, 2, 3, 4, and 5 inches. A single probe was placed in each concrete disk, and each disk was made in duplicate. A test period of over 1,505 days has shown no measurable corrosion in any of the 20 cups involved.

Experimental Walls

In order to simulate a marine environment exposure such as that encountered by a building on a tropic atoll, small walls of reinforced concrete were built and sea-water spray was applied daily. The details of the concrete mixes are shown in References 3 and 7.

The casting dates and the variables investigated are shown in Table I. Three types of aggregate, two water - cement ratios (0.444 and 0.702), and two different reinforcing-steel arrangements were employed. Each of the steel arrangements had the same number of bars and grid spacings (6 inches by 6 inches), as illustrated in

* Chlorides of alkali metals.

Figure 1. The only difference was that in one arrangement the mild steel bars were insulated from each other with plastic tape and tied together with nylon cord; in the other arrangement, the bars were tack-welded together. These two arrangements were to permit an investigation of the corrosion effect of individual steel bars as compared to the corrosion effect of an interconnected grid. Two depths of cover over the steel were also included as variables, the depth being measured from the outer surface of the concrete to the nearest surface of the steel. The steel grids were cleaned by sand blasting prior to placement of concrete.

When the walls were approximately 30 days old, the first application of seawater spray was made on one side of each wall for a 5-minute interval at 0830 each morning. This was begun on 15 June 1961. An overall view of the walls is shown in Figure 2.

Experimental Wall Results

Small spots of brownish stain were first observed on 5 September 1962 on walls No. 1, 2, 5, 8, and 10. The spots were rubbed with cotton swabs which subsequently were dissolved in hydrochloric acid and the solution treated with ammonium thiocyanate. The resulting positive test indicated the presence of ferric ion; thus, the stains were considered to be ferric oxide leaching out of the corrosion products of the reinforcing steel. On 20 February 1963 small vertical cracks were observed on the end faces of walls No. 1, 2, and 10. By 5 March 1963 every wall showed some visual evidence of rust stains.

During the ensuing months the cracks continued to widen and lengthen, and additional cracks developed in walls 1, 2, 6, 10, and 11. The detailed history of the walls together with appropriate photographs are given in the Appendix.

As may be noted in Table II, the location of cracking was not consistent. Walls 1, 2, and 10 first revealed significant cracking (vertically) on the narrow end faces. It was many months later before significant cracking occurred on the larger faces, such as the horizontal cracking on the north face of wall No. 2. (The orientation of the walls is shown in Figure 2.) Wall No. 6 did not crack on the narrow end faces at all and did not reveal the horizontal cracking on the south face until very late in its history.

Horizontal cracking on the north face of wall No. 2 and on the south face of wall No. 6 is attributable to the orientation of the steel grid. The horizontal steel bars were adjacent to the face of the wall where horizontal cracking took place.

Except for wall No. 1, the 13.5-inch-thick walls have shown no significant deterioration for two reasons. The author believes the greater thickness of cover serves to delay salt penetration, and that it provides greater resistance to rupture by the forces induced by the increasing volume of corrosion products on the steel reinforcement. As of May 1965, wall No. 11 indicated that a grid pattern of cracking was developing.

Table I. Variables for Experimental Walls

Statistical Factors	Wall Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Casting Date (1961)	May 15	May 8	May 11	May 8	May 11	May 15	May 11	May 8	May 15	May 11	May 15	May 8
Aggregate ^{1/}	GMR	SG	ENR	SG	ENR	GMR	ENR	SG	GMR	ENR	GMR	SG
Strength ^{2/}	Hi	Lo	Lo	Hi	Hi	Lo	Hi	Lo	Lo	Lo	Hi	Hi
Steel Arrangement ^{3/}	T	W	T	W	T	W	W	T	T	W	W	T
Depth of Steel ^{4/} (cover), in.	1	1	6	6	1	1	6	6	6	1	6	1
Wall Thickness, in.	3-1/2	3-1/2	13-1/2	13-1/2	3-1/2	3-1/2	13-1/2	13-1/2	13-1/2	3-1/2	13-1/2	3-1/2
Permeability ^{5/}	0.272	0.302	0.158	0.135	0.100	0.335	0.100	0.302	0.335	0.158	0.272	0.135
Cement Factor ^{6/}	8.65	4.81	5.66	7.62	8.65	5.66	8.65	4.81	5.66	5.66	8.65	7.62

1/ GMR Guam reef coral — relatively poor quality
 SG San Gabriel reference aggregate — excellent quality
 ENR Eritwetok atoll reef coral — excellent quality

Maximum aggregate size: 3/4 in.

2/ Hi High; water - cement ratio = 0.444
 Lo Low; water - cement ratio = 0.702

3/ T Tied with nylon cord; steel contacts insulated
 W Welded

4/ Depth of cover as shown for the thin walls except for top horizontal bar; the vertical cover was about 6 in.

5/ Rates for water vapor transmission: grains of water per square inch of cross section per day (See References 3 and 7)

6/ Sacks of cement per cubic yard of concrete; design slump 3 in.

Table II. Chronology of Wall Cracking

Date	Wall Number 1/			
	1	2	6	10
May 61	Cast	Cast	Cast	Cast
20 Feb 63	Vertical crack on W. end face	Vertical cracks on E. and W. end faces ^{2/}	Vertical crack on E. and W. end faces	Vertical cracks (2) on S. face
5 Mar 63		Small crack on upper left corner of S. face		
23 Sept 63	Crack on lower left corner of S. face			
18 Sept 64		Horizontal cracks (2) on N. face		
1 Nov 64			Horizontal cracks (2) on S. face	
23 Feb 65	Vertical crack on E. end face			Hairline grid cracking on S. face Small cracks on E., W., & S. faces

1/ Orientation of walls shown in Figure 2; sea spray applied to south face.

2/ Barely visible on 5 Sept 62.



Figure 1. Grid of No. 5 reinforcing bars. This grid is held together with nylon cord. The points of contact are insulated with plastic tape.



Figure 2. Overall view of experimental walls. Line of walls is west to east from left to right.

On 14 May 1965 walls No. 1, 2, 6, and 10 were removed from the test site and the concrete was broken from the steel grids. A thorough examination of the grids showed that the percentage of steel area of each grid that corroded was about as follows: 75 percent for grid No. 1, 35 percent for grid No. 10, 60 percent for grid No. 6, and 65 percent for grid No. 2. Powdery as well as flaky corrosion products were present. Considerable migration of corrosion products had taken place in the concrete.

There were many scattered areas of corrosion on grid No. 1, ranging from light staining to deeply affected areas similar to local action cells. Vertical as well as horizontal bars were affected; the corroded areas varied in length from 1 to 8 inches along the bars. A vertical end bar was the one most seriously corroded.

On grid No. 10, the vertical bars on either end had almost 100 percent of the area corroded. On the other bars, there were areas of rust ranging in length from 0.5 to 4 inches. The local corrosion areas were spaced somewhat randomly; they were not concentrated at the welds. The vertical bars on each end of grid No. 6 were thickly coated with rust. The four inner vertical bars were practically free of rust; however, rusting was severe on the four lower horizontal bars.

On grid No. 2, the upper horizontal bar and the two vertical end bars were corroded over nearly all of their surfaces. There were scattered areas of rust on the remaining bars with definitely more rust on the horizontal bars, the areas extending in length from 2 to 22 inches.

The factors of the five walls showing comparatively significant deterioration may be noted in Table III. The walls are listed in decreasing order of deterioration. This listing was made by two civil engineers examining the walls without knowledge of the particular design for each wall. Therefore, it is considered to be relatively unbiased. The author could find no room for disagreement.

Of the five walls that showed significant cracking caused by corrosion of the embedded steel, the following may be noted: five walls were of comparatively low-strength concrete; four had a 1-inch depth of concrete cover over steel; four had welded steel grids; three were made using poor aggregate; and five had permeability ratings of 158 or higher. Of the seven walls that showed no significant cracking, six were made using good aggregate; five had a 6-inch depth of concrete cover over steel; five had insulated steel grids; and four had high-strength concrete. Two of the seven walls had permeability ratings greater than 158; however, they were thick walls.

Originally the experimental design was proposed to determine the separate effects of aggregate, water-cement ratio (strength), steel arrangement, and depth of steel on the durability of small walls. A half-replicate fractional factorial experiment was proposed involving only 12 of the possible 24 combinations of the above four factors. The choice of experimental design was influenced by limited quantities of GMR and ENR aggregates on hand as well as the anticipated method of analysis of results of wall deterioration. It was believed that spalling and cracking would predominate on the surfaces of the wall receiving sea-water spray, and a suitable photographic analysis as a function of time could be made. Since this did not result, it is not so easy to draw firm conclusions.

Table III. Rating of Condition of Walls, 10 May 1965

Wall No. ^{1/}	Aggregate		Concrete Strength ^{2/}		Steel		Cover on Steel		Permeability Rating ^{4/}
	Poor	Good	Low	High	Insulated ^{3/}	Welded	1 in.	6 in.	
These walls show significant cracking									
2		X	X			X	X		302
10		X	X			X	X		158
1	X		X		X		X		272
6	X		X			X	X		335
11	X		X			X		X	272
These walls do not show significant cracking									
9	X		X		X			X	335
7		X	X	X		X		X	100
3		X	X		X			X	158
4		X		X		X		X	135
8		X	X		X			X	302
12		X		X	X		X		135
5		X		X	X		X		100

1/ Arranged in order of deterioration; e.g., wall 2 is in worst condition, wall 5 is in best condition.

2/ High strength about 8,500 psi at 448d field cure for SG and ENR; about 5,500 psi for GMR (see Reference 3).
Low strength about 5,200 psi at 448d field cure for SG and ENR; about 2,200 psi for GMR (see Reference 3).

3/ Each bar insulated from direct contact with any other bar.

4/ As a ratio to least value of permeability of 0.100, rating = 100.

Based on Table III, if an engineer had only poor aggregate available, he would probably be cautious about weldments in the reinforcing bars, he would want to use higher strength concrete and perhaps increase the cover over the steel. Precise values for these variables is a matter of engineering judgment. Poor aggregate, of course, is not a desirable choice. In fact, four of the GMR aggregate concrete walls failed and the fifth is in the worst condition of those walls that have not shown cracking. It is notable that the two best walls have only 1 inch of cover over the steel and the steel grids are not welded; however, they did employ good aggregate and high-strength concrete. Moreover, they had very low permeability factors.

In the overall picture, the ratio of failures to totals by factors (taking Note 2 of Table III into consideration) is as follows:

<u>Factors</u>	<u>Failures</u>
Poor aggregate	3 out of 4
Good aggregate	2 out of 8
Low strength	5 out of 8
High strength	0 out of 4
Insulated steel	1 out of 6
Welded steel	4 out of 6
One-inch cover	4 out of 6
Six-inch cover	1 out of 6

In general it might be concluded that deterioration of the walls is most closely associated with (1) poor-quality aggregate, (2) the lower concrete strength, (3) weldments in steel grids, and (4) the thinner walls.

It is believed the thicker walls generally would outlast the thinner walls for two reasons. It should take longer for salt water to penetrate to the steel in the thicker wall — six times as far to go in the thicker wall than the thin wall. Also, the thicker wall would have greater total resistance to cracking than would the thinner wall for the same magnitudes of internal forces caused by a build-up of corrosion products.

Cracking of walls No. 1, 2, and 10 occurred in slightly less than 2 years. This corresponds very closely with the time required for similar deterioration of buildings on Midway.¹

DISCUSSION

Findings of the investigations at NCEL confirm what has long been suspected by many concrete corrosion technologists; that is, corrosion of reinforcing steel in concrete will not readily occur in a marine environment if the concrete is initially salt free and has low permeability. Impermeable concrete is associated with high-strength (low water - cement ratio) and high-quality concrete.³ Degree of permeability has reference to the ability of water in any form to pass through hardened concrete.

In order to build a structure of high-quality concrete, the greatest care must be exercised in every one of the following generalized operations:

1. Design of the concrete mixture
2. Selection and processing of the constituents
3. Placement of reinforcing steel to assure adequate and uniform depth of concrete cover
4. Rigid supervision and controls in the production, transportation, placement, and compaction of freshly mixed concrete
5. Curing of concrete

Corrosion may sometimes be controlled by the introduction of a compound that counteracts either the anodic or cathodic corrosion reactions; however, the presence of chloride or sulfate greatly impairs the action of all inhibitors.⁸ Therefore, to be effective, a greater quantity of inhibitor is required in concrete containing salt than otherwise. Before any inhibitor is used, its effect on concrete per se should be investigated.

Corrosion of steel in salt-free concrete does not appear to be a problem even where the water content of the concrete is at a high level. For example, concrete sealed in the wet cups had water available continuously, and no corrosion of embedded steel was detected in salt-free concrete.

RECOMMENDATIONS

In the author's opinion, the most desirable solution to the problem is first to keep out the salt and second to take steps to assure that it stays out. The first part can be accomplished by washing with fresh water all aggregates contaminated with salt and by using only fresh water as the mixing water. The second part is not so easy. An impervious transparent membrane over the concrete exterior would be most desirable; however, according to several manufacturers' representatives, no such product has been developed that can be economically applied to concrete. Pending the development of an economical impervious and transparent coating, the engineer has no choice other than to use the highest quality concrete that is economical.

Appendix

HISTORY OF WALLS

Sea water was first sprayed on the south faces of the walls on June 15, 1961 and thereafter daily for a 5-minute period at approximately 0800 to 0805. The orientation of the walls is shown in Figure 2.

Wall No. 1 — See Figures 3, 4, and 5

1961 - May 15	Casting date.
1962 - Sept 5	Brown stains (spots) apparent on east end face and on upper left of north face.
1963 - Feb 20	Crack on west end face was noticeable. See Figure 3.
1963 - Mar 5	Brown stains (spots) apparent on south face.
1963 - Sept 23	Vertical crack apparent on lower left corner of south face. See Figure 4.
1965 - Feb 23	Crack on east end face. See Figure 5.

Wall No. 2 — See Figures 6, 7, 8, and 9

1961 - May 8	Casting date.
1962 - Sept 5	Brown stains (spots) on both end faces and on upper middle of north face (6 inches from top). Hairline cracks (vertical) apparent on both end faces.
1963 - Feb 20	Cracks on end faces more noticeable. See Figures 6 and 7.
1963 - Mar 5	Cracks on end faces more extensive. Brown stains (spots) on all faces except top. Small curved crack in upper left-hand corner of south face. See Figure 8.
1964 - Sept 18	Two horizontal cracks apparent on north face. See Figure 9.

Wall No. 3

1961 - May 11	Casting date.
1963 - Mar 5	Brown stains (spots) on east, west, and south faces.
1965 - Feb	No cracks to date.

Wall No. 4

1961 - May 8	Casting date.
1963 - Mar 5	Brown stains (spots) on east, west, and south faces.
1965 - Feb	No cracks to date.

Wall No. 5

1961 - May 11	Casting date.
1962 - Sept 5	Brown stains (spots) on east, west, and north faces.
1963 - Mar 5	Additional stains on all faces except top.
1965 - Feb	No cracks to date.

Wall No. 6 — See Figure 10

1961 - May 15	Casting date.
1963 - Mar 5	Brown stains (spots) on east and west end faces and on south face.
1964 - Nov 1	Two horizontal cracks on south face. See Figure 10. Faint traces of these cracks are visible in a photograph taken 2 Jan 1963.

Wall No. 7

1961 - May 11	Casting date.
1962 - Sept 5	Hairline cracks on top surface extending a short distance down on north and south faces.
1963 - Mar 5	Brown stains (spots) on all faces except top; additional hairline cracks similar to those of 5 Sept 1962.
1965 - Feb	No significant cracking to date.

Wall No. 8

1961 - May 8	Casting date.
1962 - Sept 5	Brown stains (spots) on top surface.
1963 - Mar 5	Stains on south face.
1965 - Feb	No cracks to date.

Wall No. 9

1961 - May 15	Casting date.
1962 - Sept 5	Hairline cracks on top surface extending a short distance down on north and south faces.
1963 - Mar 5	Brown stains (spots) on top surface and on north, south, and east faces.
1965 - Feb	No significant cracking to date.

Wall No 10 — See Figures 11, 12, 13, and 14

1961 - May 11	Casting date.
1962 - Sept 5	Brown stains (spots) on west end face.
1963 - Feb 20	Crack on west end face. See Figures 11 and 12. Crack on east end face. See Figure 13.
1963 - Mar 5	Additional brown stains on both end faces and also on south face.
1963 - Sept 23	Two vertical cracks, each about 5 inches long appeared on south face, one adjacent to east edge and one adjacent to west edge. See Figure 14.

Wall No. 11 — See Figures 15, 16a, 16b, and 17

1961 - May 15	Casting date.
1962 - Sept 5	Hairline crack on top surface extending a short distance down on south face.
1963 - Mar 5	Brown stains (spots) on south face.
1964 - Nov 1	Hairline grid-cracking on south face corresponding approximately to steel grid. See Figure 15.
1965 - Feb 23	Cracks on east and west faces. See Figures 16a, 16b, and 17.

Wall No. 12

1961 - May 8

Casting date.

1963 - Mar 5

Brown stains (spots) on all faces except top.

1965 - Feb

No cracking to date.

REFERENCES

1. Indenco Engineers, Inc. Engineering study on Contract NBy-27355, prepared for DPWO Fourteenth Naval District: Recommendations and estimates for repair to AEW facilities at U. S. Naval Station, Midway Island. San Leandro, Calif., Mar. 1960.
2. J. D. Babbitt. "The movement of moisture through solids," ASTM Bulletin, no. 212, Feb. 1956, pp. 58-60.
3. D. F. Griffin and R. L. Henry. "Effect of salt in concrete on compressive strength, water vapor transmission, and corrosion of reinforcing steel," American Society for Testing and Materials, Proceedings, vol. 63, 1963, pp. 1046-1078.
4. U. S. National Bureau of Standards. Technologic Paper T-18: Electrolysis in concrete, by E. B. Rosa, B. McCollum, and O. S. Peters. Washington, D. C., 1913.
5. F. L. LaQue and H. R. Copson, eds. Corrosion resistance of metals and alloys, 2nd ed. New York, Reinhold, 1963.
6. H. H. Uhlig. Corrosion handbook. New York, Wiley, 1948.
7. U. S. Naval Civil Engineering Laboratory. Technical Report R-306: The effect of salt in concrete on compressive strength, water vapor transmission, and corrosion of reinforcing steel, by D. F. Griffin and R. L. Henry. Port Hueneme, Calif., July 1964.
8. P. Hersch, et al. "An experimental survey of rust preventatives in water," Journal of Applied Chemistry (London), vol. 11, July 1961, pp. 246-271.



(a) 20 Feb 1963
First observed

(b) 14 Oct 1963

(c) 2 Dec 1964

Figure 3. Wall No. 1, west end face. Progression of cracking.

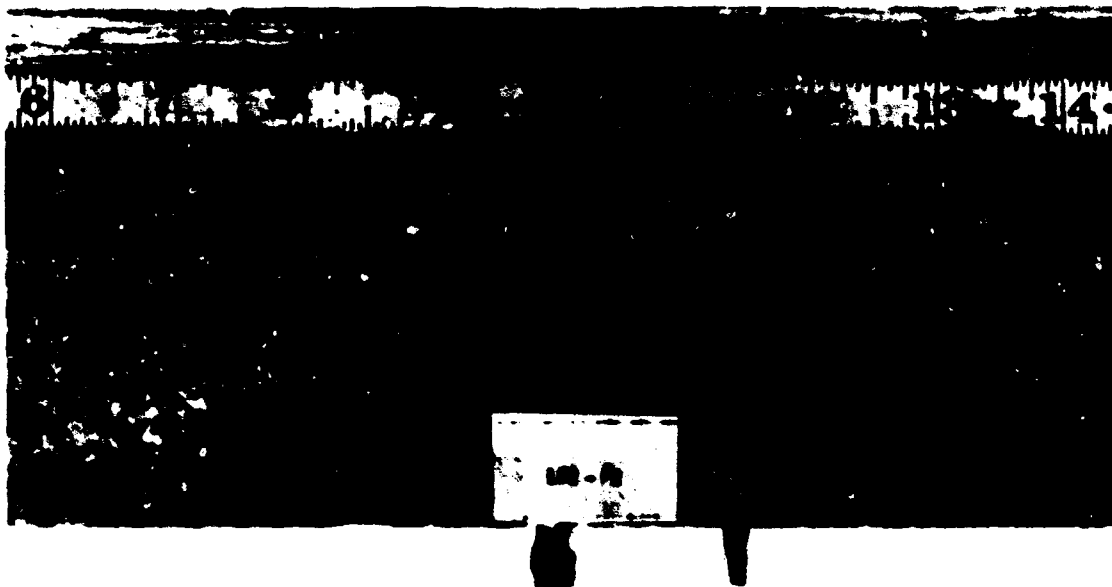
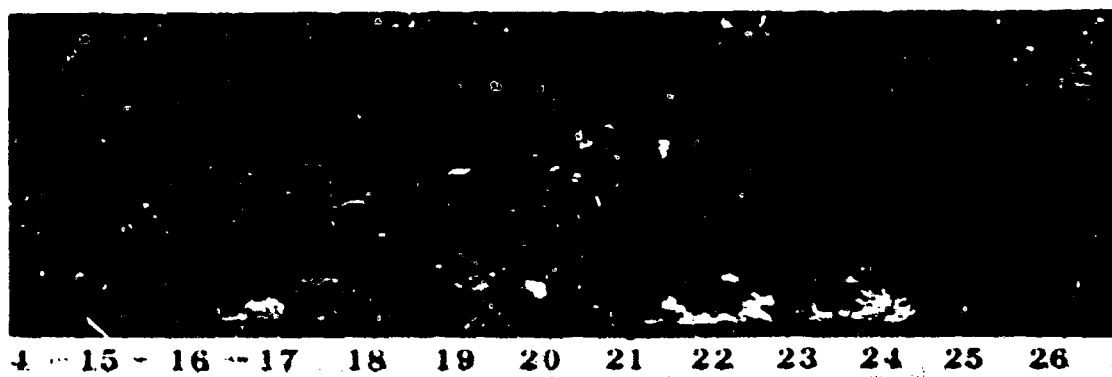
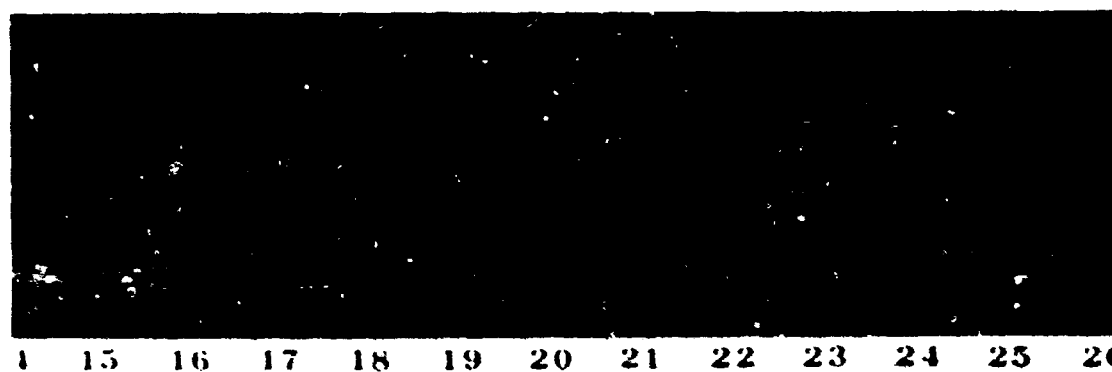


Figure 5. Wall No. 1, east end face.
Crack first noticed 23 Feb 1965.

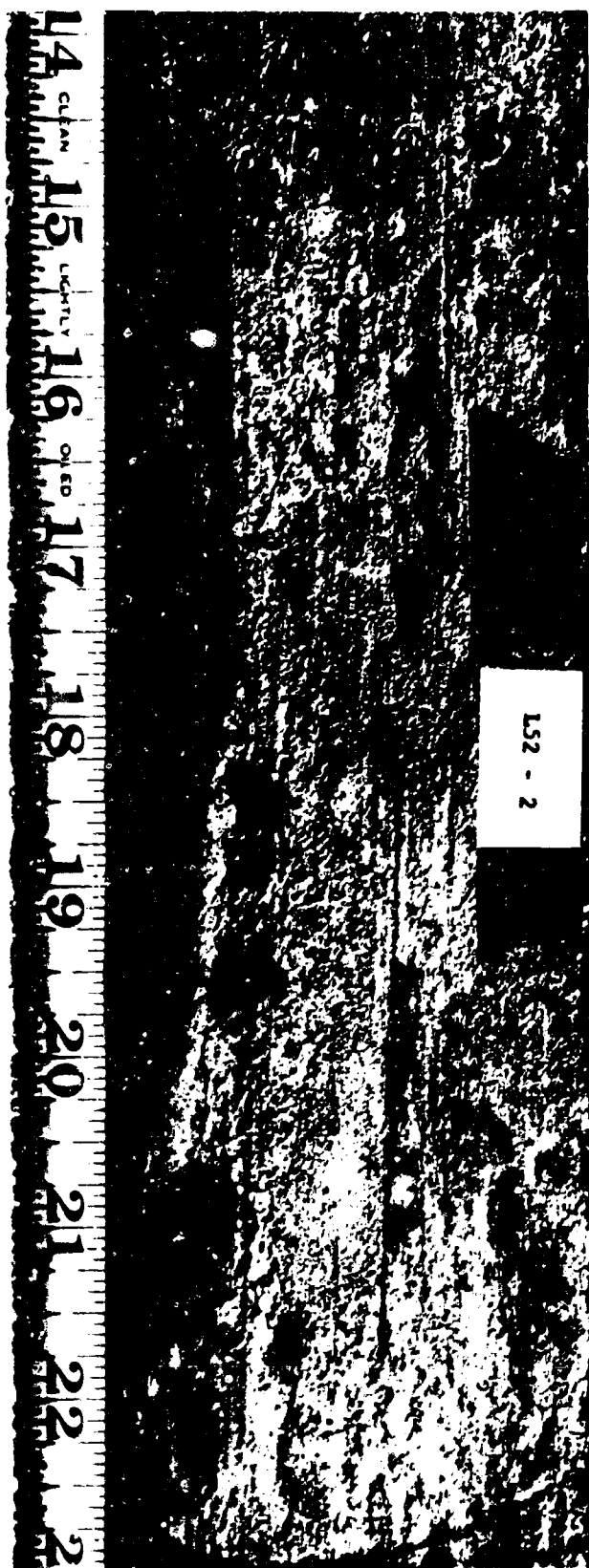


(w) 1 Nov 1964

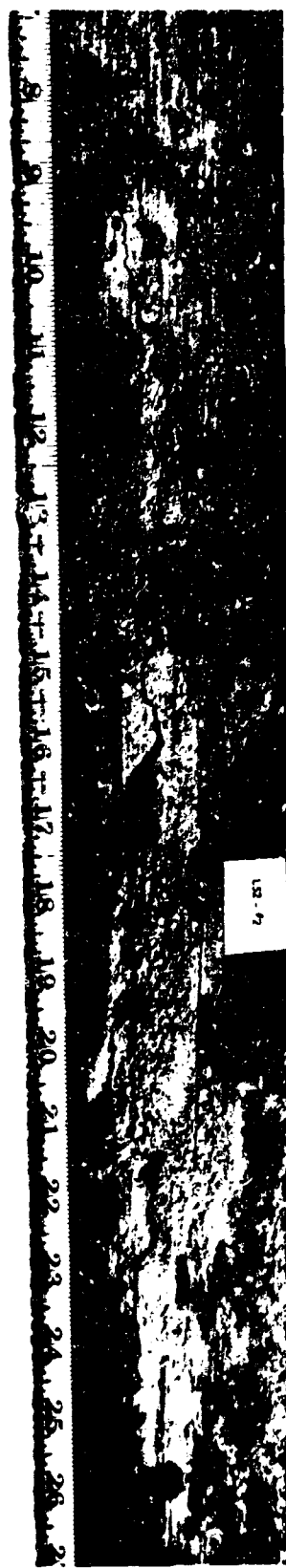


(a) 14 Oct 1963

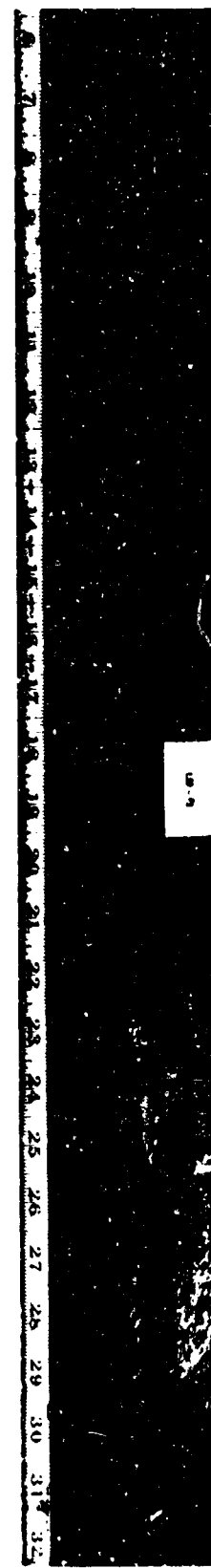
Figure 4. Wall No. 1, south face. Progression of cracking
first observed 23 Sept 1963, adjacent to west end.



(a) 20 Feb 1963



(b) 29 Nov 1963



(c) 2 Dec 1964

Figure c. Wall No. 2, east end face. Progression of cracking first observed 5 Sept 1962.

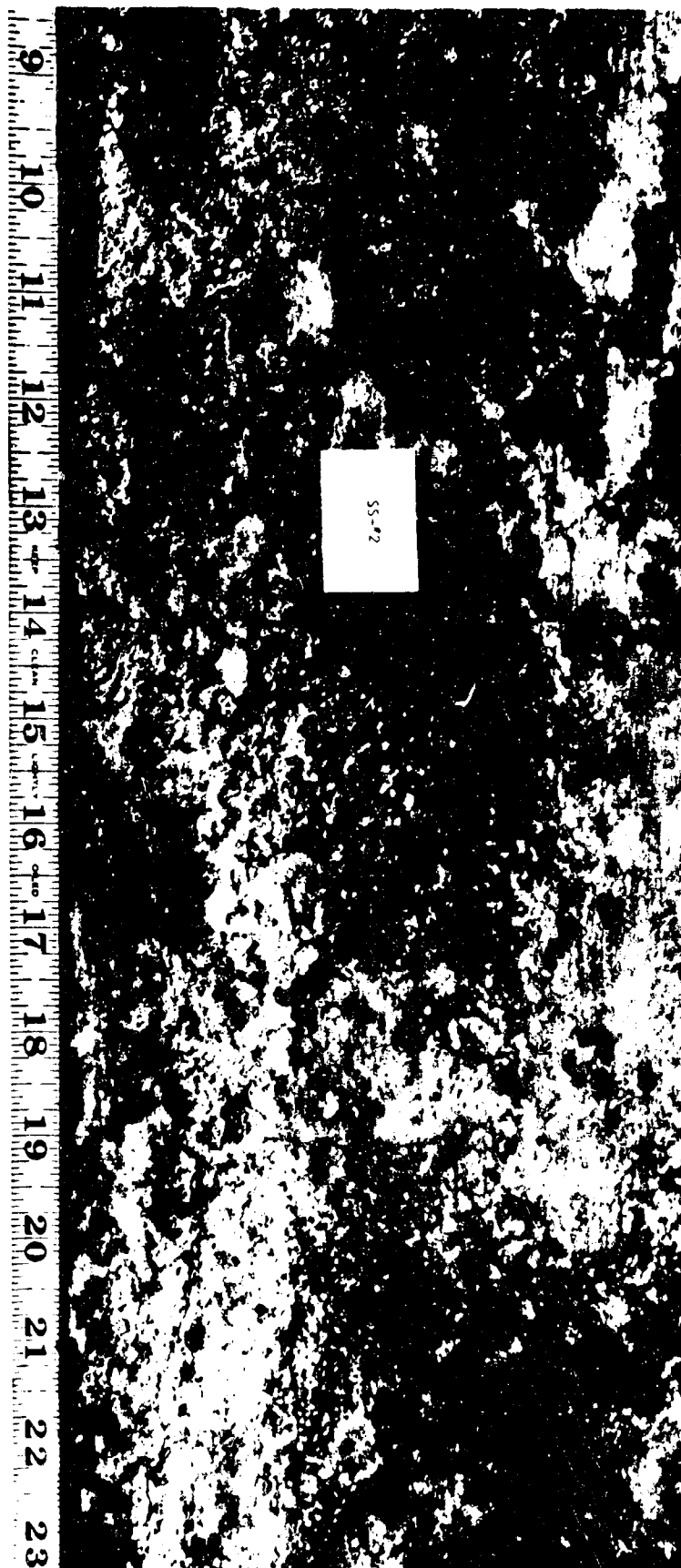


(a) 20 Feb 1963

(b) 29 Nov 1963

(c) 2 Dec 1964

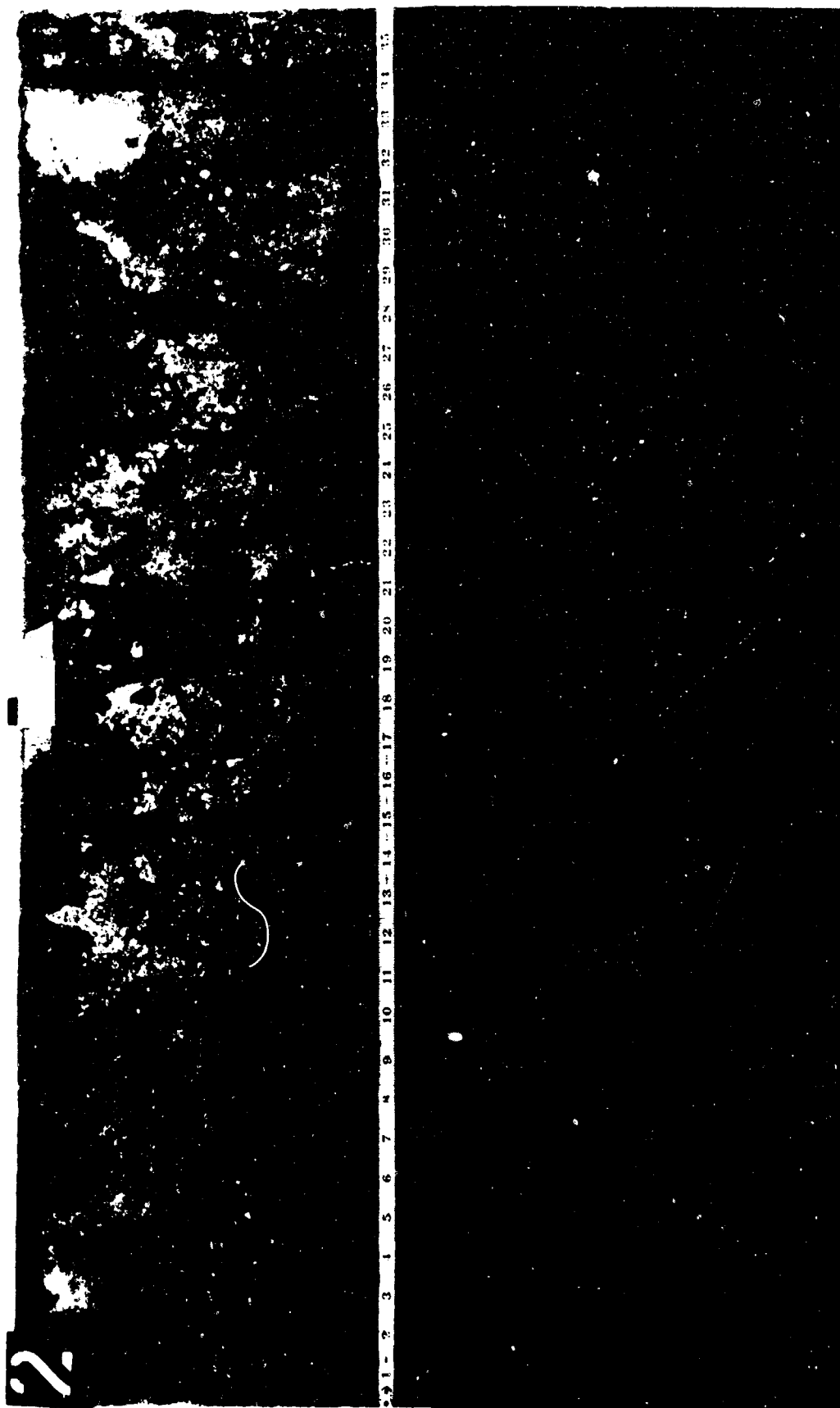
Figure 7. Wall No. 2, west end face. Progression of cracking first observed 5 Sept 1962.



2 Dec 1964

First observed between
9 and 11 in. on 5 Mar 1963

Figure 8. Wall No. 2, south face. Vertical crack on left side about the same as when observed 18 Sept 1964.



2 Dec 1964

Figure 9. Wall No. 2, north face. Two horizontal cracks are about the same as when first observed on 18 Sept 1964. Cracks are opposite first and second bars (from top) shown in Figure 1.

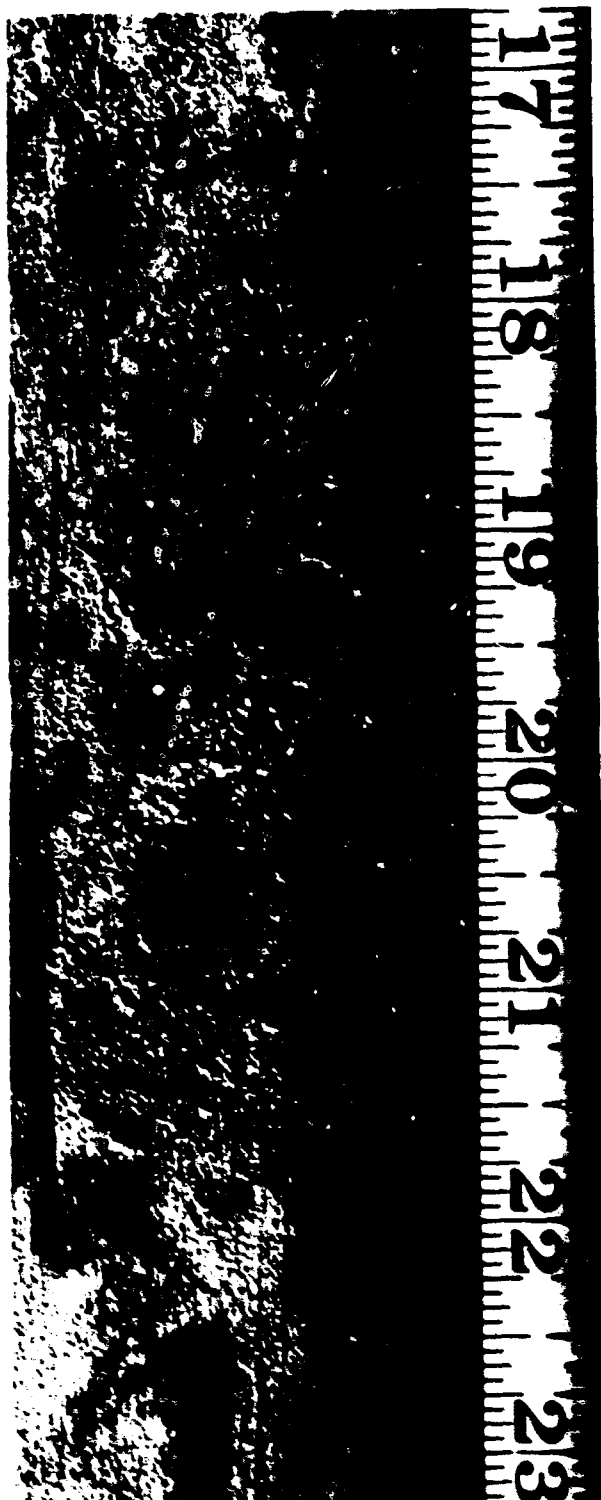


2 Dec 1964

Figure 10. Wall No. 6, south face, showing two horizontal cracks about the same as when first observed 1 Nov 1964. Cracks are opposite second and third bars (from top) shown in Figure 1.

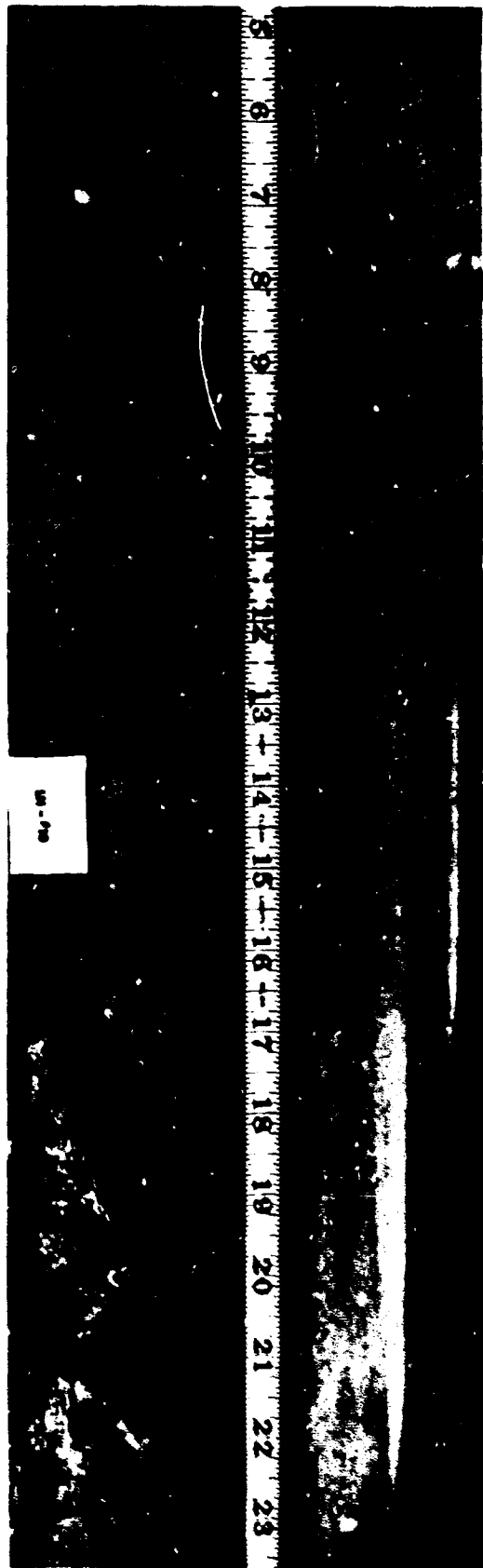


(a) 20 Feb 1963
Crack from 8 to 13 in. below top

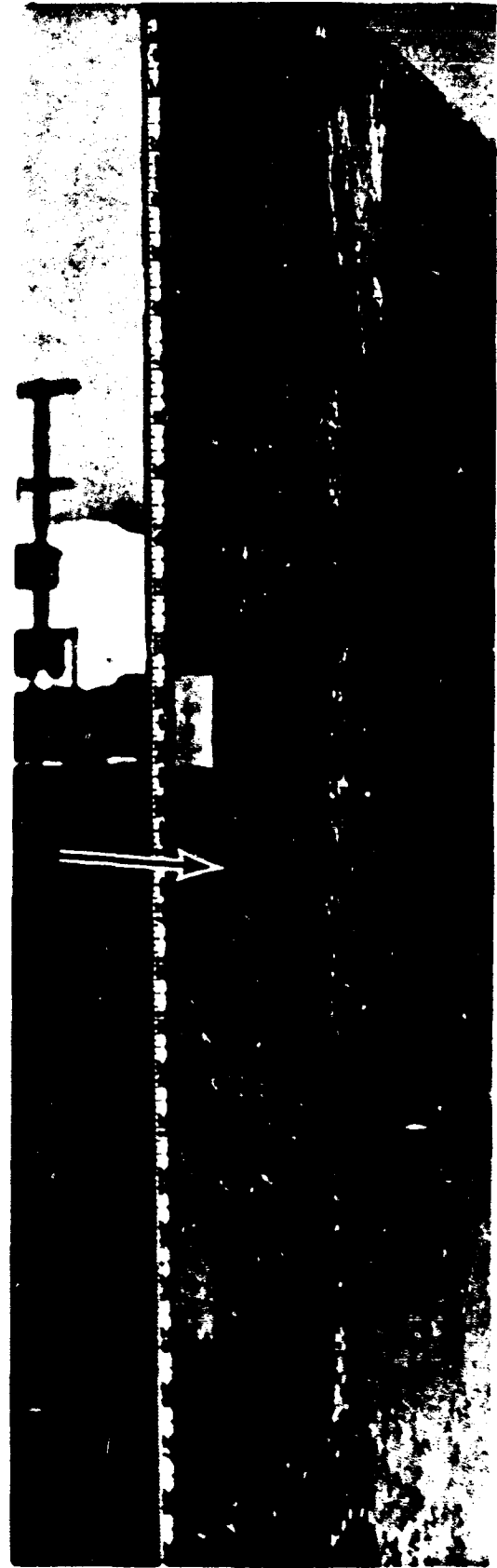


(b) 20 Feb 1963
Crack from 17 to 23 in. below top

Figure 11. Wall No. 10, west end face.



(a) 14 Oct 1963



(b) 2 Dec 1964

Figure 12. Wall No. 10, west end face. Progression of cracks shown in Figure 11. Arrow shows additional crack.



(a) 20 Feb 1963

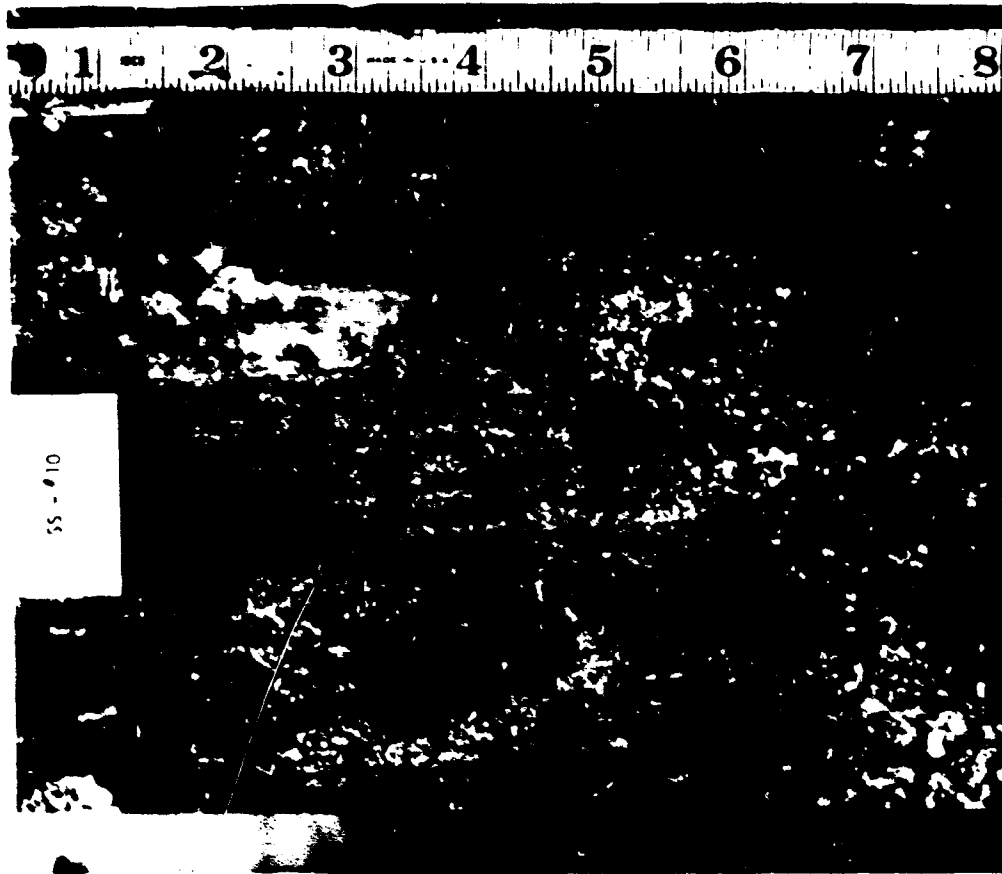


(b) 14 Feb 1964

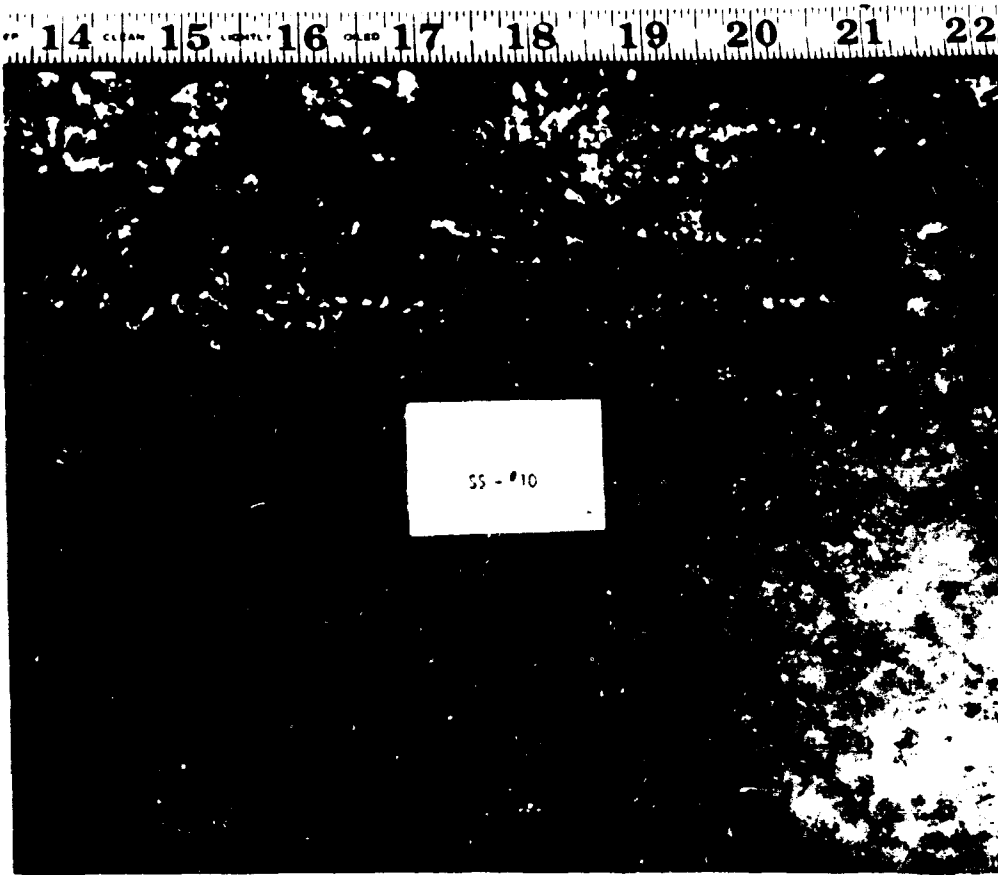


(c) 2 Dec 1964

Figure 13. Wall No. 10, east end face, showing progression of crack.



(a) Crack adjacent to west end on 2 Dec 1964



(b) Crack adjacent to east end on 2 Dec 1964 —
first noticed 18 Sep 1964, with very little
progression to date

Figure 14. Wall No. 10, south face.



Figure 15. Wall No. 11, south face, showing hairline grid cracking as of 2 Dec 1964.

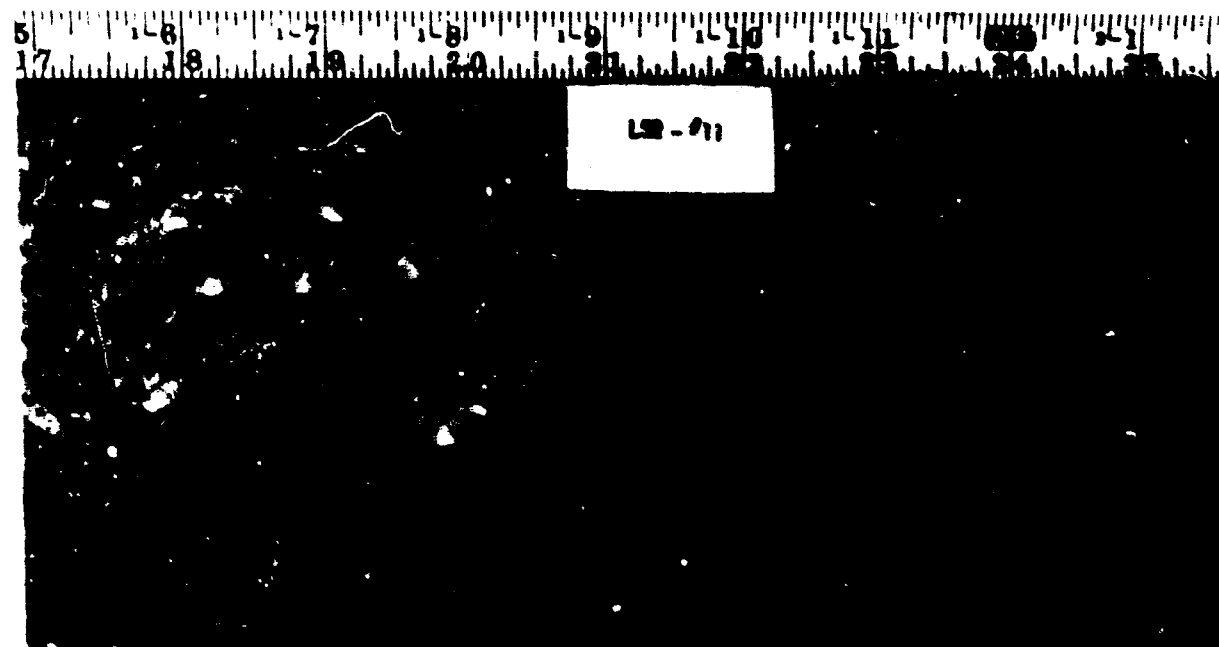


Figure 16a. Wall No. 11, east end face.
Crack first noticed 23 Feb 1965.

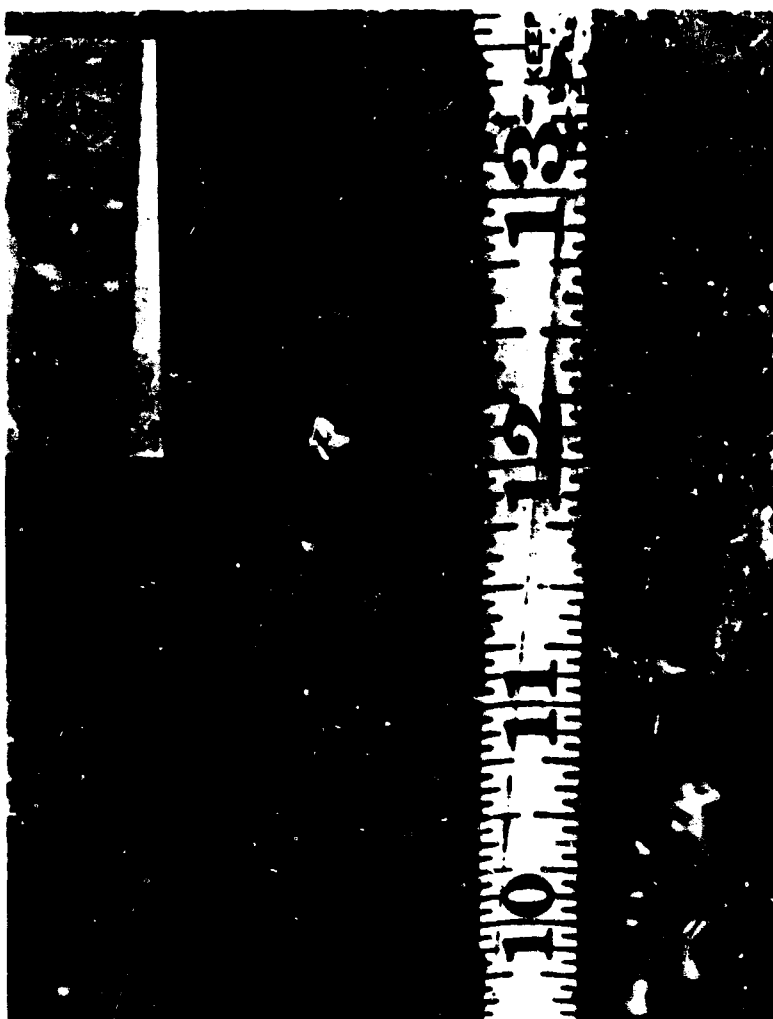


Figure 16b. Wall No. 11, east end face Horizontal crack
about 8 inches below top surface of wall. Crack
first noticed 23 Feb 1965.

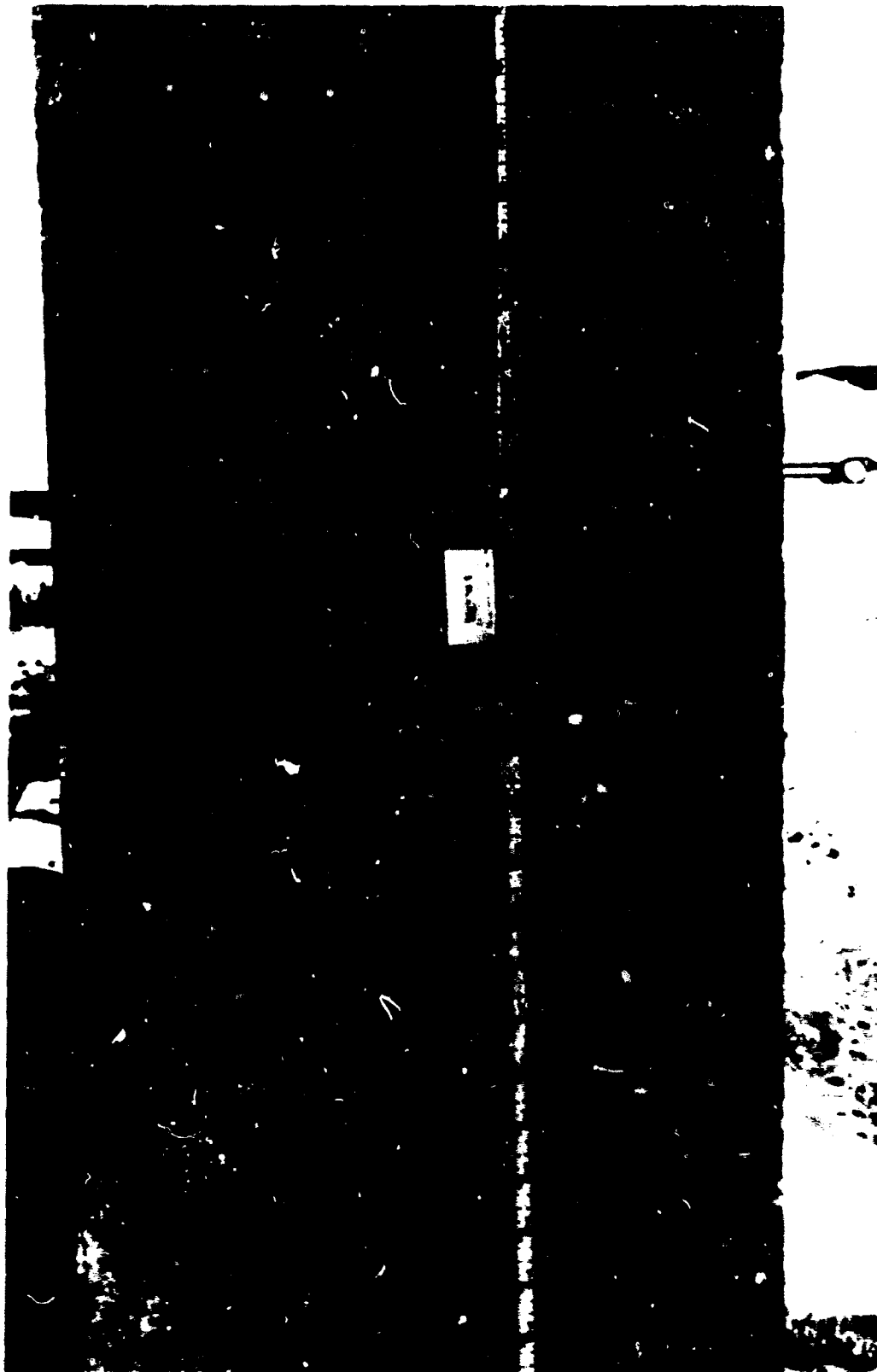


Figure 17. Wall No. 11, west end face. Vertical crack following about 1/2 inch to left of dashed line; also, note horizontal crack at the 11-inch mark. Cracks first noticed 23 Feb 1965.